TECHNICAL REPORT: NAVTRAEQUIPCEN IH-265

COMPUTER SIMULATION OF FRESNEL LENS OPTICAL LANDING SYSTEM

COMPUTER LABORATORY
NAVAL TRAINING EQUIPMENT CENTER
ORLANDO, FLORIDA 32813

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COMPUTER SIMULATION OF FRESNEL LENS OPTICAL LANDING SYSTEM

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This report describes a computer simulation of a Fresnel Lens Optical Landing System (FLOLS). The simulation was a subtask of a carrier landing visual simulation. A description of the math model for duplicating the appearance and behavior of the real FLOLS system is provided. The computer generated visual display of the FLOLS was produced through an Evans & Sutherland Computer Corporation LDS-1 (Line Drawing System Model 1) calligraphic display system.

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INTRODUCTION

The computer simulation of a Fresnel Lens Optical Landing System (FLOLS) at the Naval Training Equipment Center (NAVTRAEQUIPCEN) graphic display installation is described in this report. The graphic installation is a part of Training Device Computer (TRADEC), the NAVTRAEQUIPCEN research facility for flight simulation, and includes an Evans & Sutherland Computer Corporation LDS-1 (Line Drawing System Model 1) for the generation of calligraphic displays.

The FLOLS simulation was a subtask of a carrier landing visual simulation on the TRADEC facility. The carrier landing program has been utilized in the investigation of visual system requirements for flight simulators.

The Fresnel system is an electrooptical landing system for use on aircraft carriers. The model for this simulation was the FLOLS MK 6 MOD 1, which is a standard CV and CVA aircraft carrier optical landing system in the Navy.

The simulation in this report was not designed by the author. Consequently, functional analyses, design specifications, and programming design documents have not been included.

The report is a description of two systems: the real system, and its synthesized counterpart. A mathematical model is provided for duplicating the appearance and behavior of the real FLOLS through digital computation. The computer program listings and all references cited are available for inspection at the Computer Laboratory, Code N-214, Naval Training Equipment Center, Orlando, Florida.

SECTION II

TRADEC SIMULATION FACILITY

The TRADEC real-time digital simulation facility is utilized by the NAVTRAEQUIPCEN in its research efforts in training device technology and advanced simulation concepts. It consists of a Xerox Data Systems Sigma 7 digital computer with 49,152 words of magnetic core memory; general-purpose peripheral equipment including keyboard printer, punched tape system, card system, magnetic disk and tape storage, and a high-speed line printer; a four-degree-of-freedom motion platform; a variable configuration simulated aircraft cockpit which is mounted on the motion platform; an operator's control console; special analog input/output and discrete interfaces; and two separate computer-generated display systems functioning independently of each other.

Presently the cockpit is configured like that of an F4 Phantom aircraft. The instructor's console is equipped with the same flight and engine instruments that are in the cockpit. The instructor's console also provides a bank of push-button indicator switches which can be utilized as pure indicators or as switches. These permit an interface with a simulation program and can be utilized in whatever fashion may be desired.

Both display systems provide line-drawing or stroke-drawing (calligraphic) display capabilities to the simulation facility. The first system is an Information Displays Incorporated Input/Output Machine (IDIIOM), and is used primarily for instructor station control applications. The IDIIOM consists of a Varian DATA 620/i digital computer, a special computer interface to the Sigma 7, a display processing unit, function generators, and two display consoles with light-pens, programmable function buttons, ASR teletypewriters, and graphic input tablet.

The second display system, an Evans & Sutherland Computer Corporation LDS-1 (Line Drawing System Model 1), is designed for out-of-the-window picture presentations of the external environment. The picture will change in direct response to the motion of the simulated aircraft, providing the simulator pilot with a dynamically changing view of the surrounding world. The LDS-1 consists of a display processor for interpreting drawing commands, a hardware matrix multiplier and clipping divider for real-time transformations on display data, and a line generator to convert digital data to analog deflection and intensity signals for two cathode ray tube (CRT) terminals. One of these terminals is in the cockpit, while a second one is at the instructor's console. References 1, 2, and 3 provide further details on the TRADEC simulation facility.

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1 M. Fischer, F.R.Cooper,"Training Device Computer Facility Dedicated at Orlando," Training Device Developments, NAVTRADEV P-1300-51, NTEC, Orlando, Florida, February 1970.

2 J.L.Booker,"Computer Generated Display System," Training Device Developments, NAVTRADEV P-1300-55, NTEC, Orlando, Florida, June 1971.

3 Evans & Sutherland Computer Corporation,"Line Drawing System Model 1, 32 Bit,System Reference Manual," Salt Lake City, Utah, December 1, 1971.

SECTION III

CARRIER LANDING SIMULATION

The simulator software currently available on the TRADEC system is a program which simulates the F4E aircraft. The F4E simulator can be utilized in the conduct of research in various aspects of simulation techniques and of human factors relating to simulation. The flight simulation provides closed-loop control functions to the simulator pilot in the cockpit. The Sigma 7 computer program provides the necessary real-time solutions to the aircraft flight equations.

A second program, running concurrently with the F4E simulation program, provides a visual simulation of an aircraft carrier in a landing exercise. This program generates a true-perspective out-of-the-window view of an aircraft carrier on the cockpit display scope. The picture moves in accordance with the aircraft attitude and flight path as the aircraft approaches the carrier. A completely nonprogrammed flight path allows the pilot complete control of his flight maneuvers. The cathode ray tube presents a 19 degrees horizontal by 19 degrees vertical field of view to the simulator pilot.

The picture is composed of connected lines which form a stick-like figure of a carrier, as in figure 1. The display also includes a simulated horizon line as an indication of the aircraft attitude to the pilot. The three-dimensional world for the display system is composed of a data base containing X, Y, Z coordinates of the end points of all connected lines. The simulation program determines the position and direction of view for the display, eliminates all lines not visible in the cone vision from the cockpit, computes a two-dimensional perspective picture of the visible lines, and generates a picture of the data base as seen through the front window of the aircraft cockpit.

References 4, 5, and 6 provide detailed descriptions of the carrier landing simulation. References 7 and 8 describe two experiments that have been conducted with this simulation program.

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4 P.A. Kapsis, M.J. Poor, J.H. Gottschalk, H.J. Wychorski, R.McDowell, "Software Documentation for the Research Tool Digital Computer System, Volume 1, Math Model Report," Technical Report: NAVTRADEVCEN 67-C-0196-7, September 1969.

5 I.E. Sutherland, D. Cohen, "Display Techniques for Simulation," Technical Report: NAVTRADEVCEN 70-C-0025-1, February 1971.

6 D. Cohen, "Naval Training Device Center Graphic Display Installation," unpublished internal NAVTRAEQUIPCEN Report.

7 F.R. Cooper, W.T.Harris, V.J.Sharkey, "Effects of Visual System Time Delay on Pilot Performance," 8th NTEC/Industry Conference Proceedings, Naval Training Equipment Center, Orlando, FL, November 1975.

8 S.C. Collyer, J.L. Booker, I.V. Golovcsenko, "The Investigation of Zoom vs. True Perspective in Simulated Carrier Landings," Technical Report: NAVTRAEQUIPCEN IH-266, to be published.

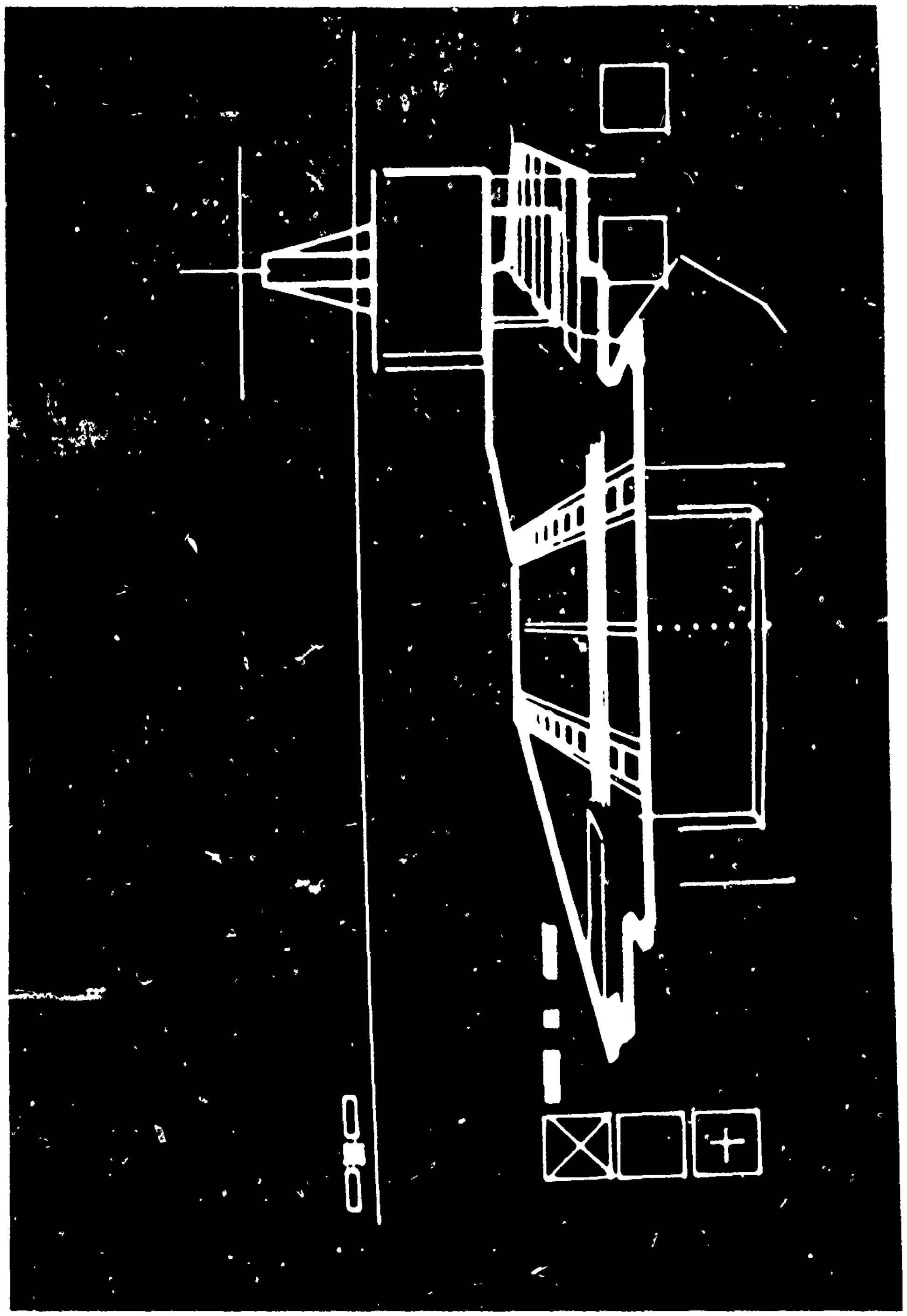


Figure 1. Computer Generated Display of Aircraft Carrier

SECTION IV

DESCRIPTION OF FLOLS

The Fresnel system is an electrooptical landing system for use on aircraft carriers. By use of the Fresnel system, the pilot whose aircraft is approaching a carrier may visually establish and maintain the proper glide slope angle for landing.

The Fresnel system provides a horizontal bar of light that appears in the source light indicators of the deck-edge assembly. The position of this bar of light with respect to a set of fixed horizontal datum lights indicates to the pilot of an approaching aircraft whether he is above, below, or on the correct glide slope. The bar of light is formed by the combined actions of source lights, Fresnel lenses, and lenticular lenses. Because of the optical system, the bar of light appears above the horizontal datum lights if the glide slope is too great, and below the horizontal datum lights if the glide slope is too small. When the pilot aligns the bar of light with the horizontal datum lights, his approach is correct for a carrier landing.

A. PHYSICAL CHARACTERISTICS

The FLOLS deck edge unit is located on the port side outboard platform opposite the island, approximately two thirds of the total runway distance forward of the ramp. The deck edge unit consists of five cell assemblies mounted in a four foot high vertical stacking (see figures 2 and 3), from which a yellow bar virtual image is produced across the cell, with an image distance of 150 feet behind the lens.[9] The arrangement of lenses with respect to the source lamps and the physical properties of the lenses cause the source lamps to appear as a common light image 12 inches wide and approximately 6 inches high. The lamps and lenses of each cell are adjusted so that the bar of yellow light seen moving up and down the face of the lens box moves smoothly from one cell to another. A horizontal row of green datum lights on each side of the indicator assembly at the center of the center cell provides the reference to which the meatball is compared. A detailed description of the FLOLS, including physical dimensions, is provided in reference 10.

When an aircraft in its approach to the carrier is dangerously low, (specifically in excess of 0.375 degrees deviation from the correct glide slope), the pilot of that aircraft views the bar of light through the red lens of the bottom (low) cell assembly. During normal operation the source lights contained in the low cell are flashing in order that the pilot may readily recognize the existence of a "red meatball condition."

9 Naval Air Systems Command, "Visual Landing Aids Design Standards; Shipboard Installation," Technical Manual: NAVAIR 51-50AAA-1, 1 June 1974.

10 Bureau of Naval Weapons, "Installation, Service, Operation and Maintenance Instructions, Fresnel Lens Optical Landing System MK 6 MOD 0," Technical Manual: NAVWEPS 51-40ABA-1, 1 October 1964.

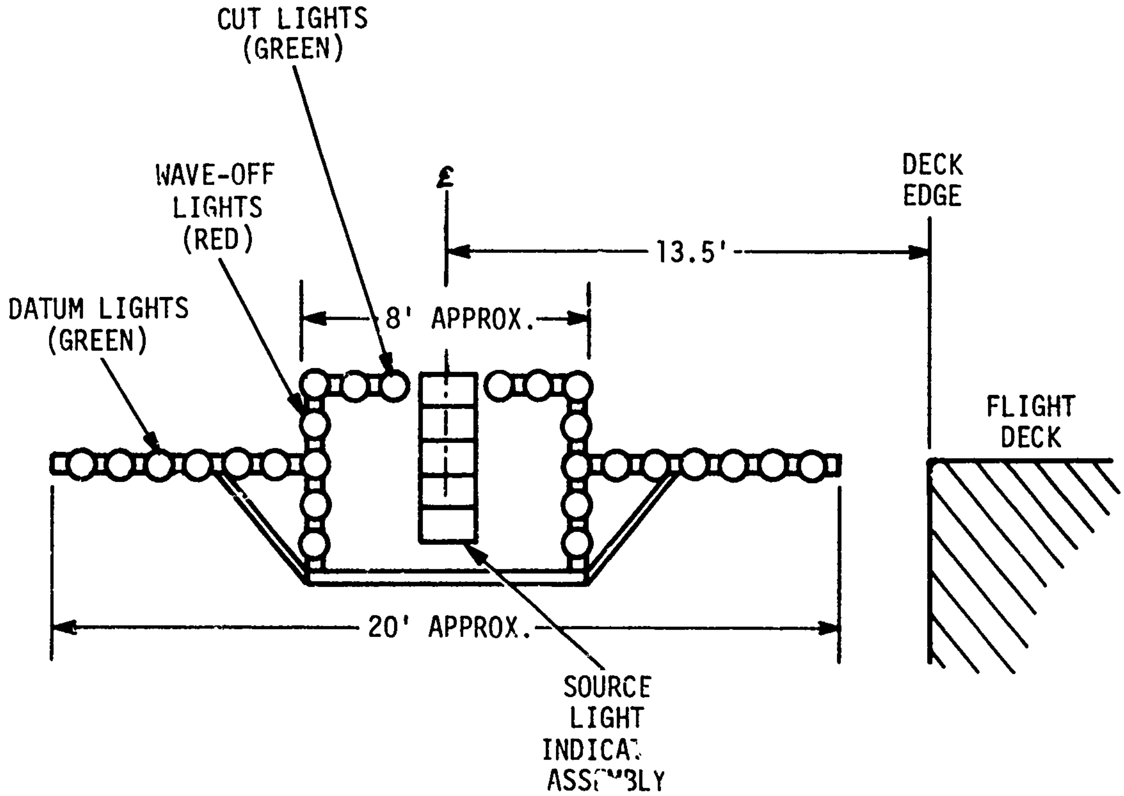


Figure 2. Typical Lens Installation.

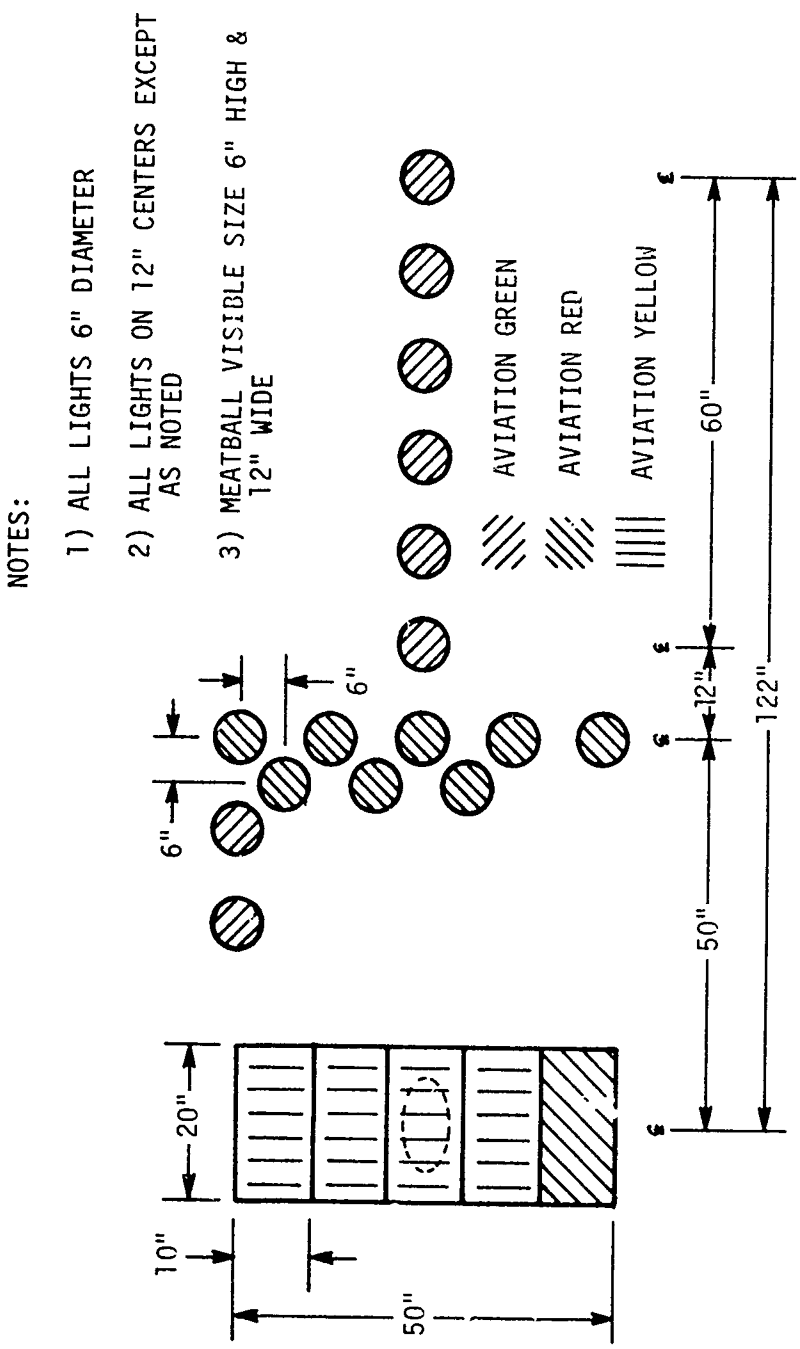


Figure 3. Typical Dimensions of Deck Edge Assembly

Vertical lines of red lights are located on each side of the lens stacking frame, as shown in figure 2. These lights are flashed simultaneously at a rate of approximately 90 flashes per minute to indicate wave-off (unsafe landing condition). In addition, a horizontal row of green lights is mounted above the lens. These lights, which do not flash, are turned on in a manner similar to the wave-off lights to indicate a "cut" to the pilot of a propeller driven aircraft

Figure 3 shows some typical dimensions for the deck edge assembly. The source light indicator assembly contains 15 source lamps in 5 separate cells. Each cell contains three source lamps arranged horizontally. As previously stated, the source lamps appear as a common light image 12 inches wide and approximately 6 inches high.

B. GLIDE SLOPE

Since different types of aircraft have different structural characteristics and capabilities, they would ideally require different glide slope angles. As a matter of practice, however, basic angle settings of 3.5 and 4.0 are most commonly used (3.5 on the east coast and 4.0 on the west coast).[11] These settings represent the basic angles that are considered to be acceptable in most recovery operations. The maximum 4-degree angle is dictated by the structual loads on the airplane imposed by the vertical sink speed. The minimum glide slope angle is dictated by several factors.[12]

a. The airplane must clear the ramp for a steady deck condition by a minimum distance of 10 feet to allow for safe ramp clearance during pitching deck conditions and pilot deviation from the desired glide slope. The length of the flight deck limits the distance that the arresting wires may be set forward of the ramp; therefore, this geometry of a ten foot ramp clearance and wire location sets a limit to which the glide slope may be lowered and still arrest the airplane.

b. The shallower the angle becomes, the greater the dispersion in touchdown with glide slope error due to the simple trigonometric relation. The ground effect for some airplane models is more pronounced on touchdown dispersion for the shallower glide slope angles.

c. It has been qualitatively determined that for the shallower angles, those of less than three degrees, pilots find it more difficult to accurately maintain desired glide slope than for the slightly steeper angles.

The total vertical angle of usable information conveyed by the FLOLS is 1.5 degrees. Plus and minus 0.75 degree deviations from the correct glide slope represents the limits within which the meatball is fully visible. Figure 4 illustrates three representative meatball positions: those for the correct glide slope, for 0.75 degrees above, and for 0.75 degrees below the correct glide slope. Three quarters of a degree above correct glide slope corresponds to the meatball being 2 meatball heights above the centered position.

11 Ibid.

12 J. H. Nelson, G. M. Griffin, "United States Navy Pilot-Controlled Landing Procedure and Associated Equipment," Report 423, NATO Advisory Group for Aeronautical Research and Development, Paris, France, January 1963.

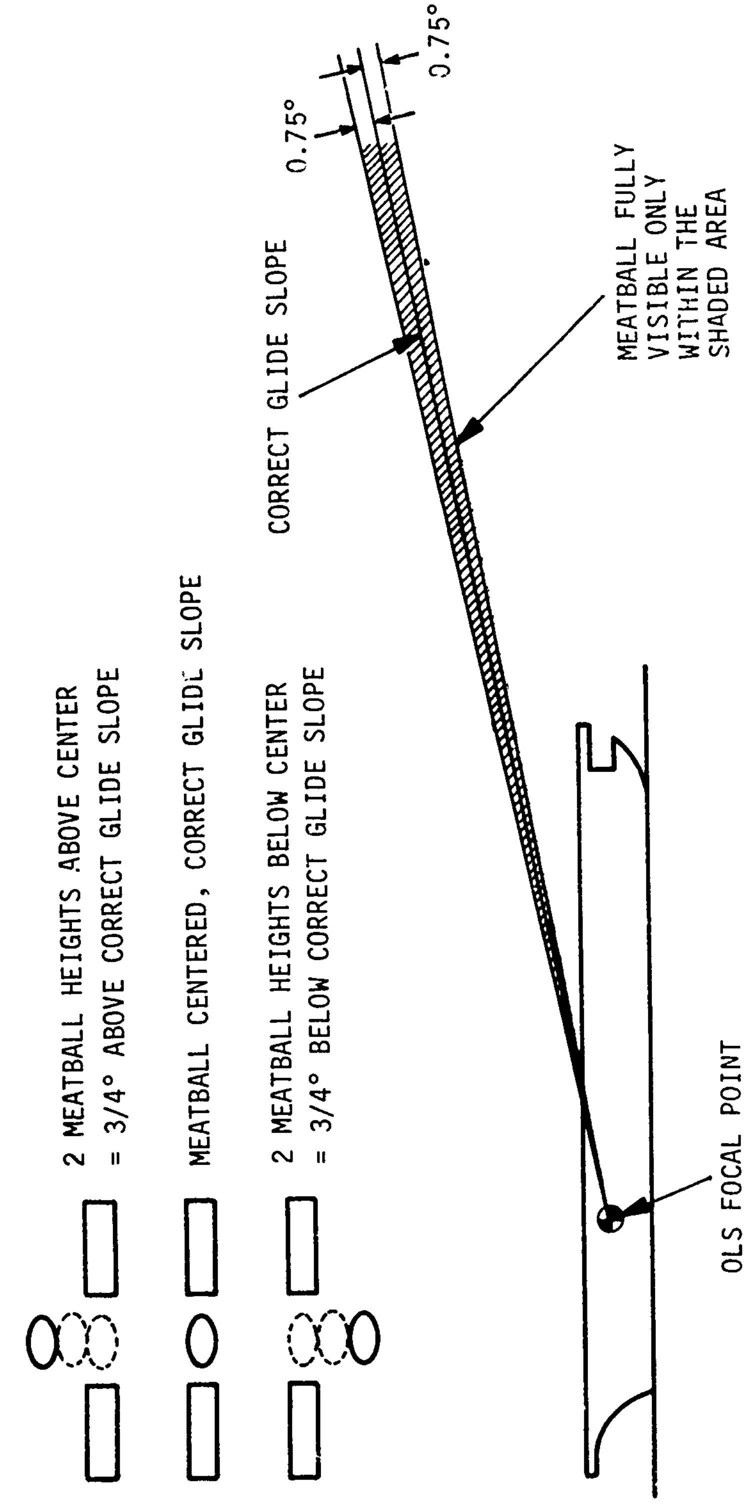


Figure 4. Correlation Between Meatball Position and Glide Slope.

Similarly, three quarters of a degree below correct glide slope corresponds to the meatball being 2 meatball heights below the centered position.

When the airplane is "in the groove" - coming down the slope with zero error trajectory -- it is the pilot's eye that is actually on the glide path. The glide path is therefore computed so that the eye-touchdown point is forward of the hook touchdown point, which is calculated to be near the no. 3 wire (see figure 5). The desired touchdown point aboard ship is normally between the second and third arresting pendants. If the error exceeds 5 feet above the desired glide slope the airplane will bolter; 5 feet below the desired glide slope places the airplane in dangerously close proximity to the flight deck ramp. Figure 5 shows that the aircraft's hook touchdown point will always be closer to the stern of the carrier than the optical touchdown point.

C. HOOK-TO-EYE DISTANCE

Although the pitch angle setting for glide slope is seldom changed, the roll angle setting is changed for each different type of aircraft to be recovered. This is necessary because of the widely varying hook-to-eye values for different types of aircraft. Figure 6 illustrates how different aircraft models have varying heights-of-eye of the pilot (called hook-to-eye distance) and require varying lens heights to give the proper hook-to-ramp clearance. Since a vertical height adjustment is necessary to accommodate differing aircraft with differing hook-to-eye dimensions, the standard FLOLS installation provides a rapid change-of-height adjustment to meet varying requirements. This is achieved by rotating the source light indicator assembly about its roll axis! The deck edge assembly includes an H/E (hook-to-eye)roll drive for rotation of the source light indicator assembly about its roll axis.

Any rotation of the light source indicator assembly shifts the optical glide slope either up or down depending on the direction in which the assembly is rotated. This shift is possible only because the physical placement of the FLOLS unit is not directly at the angled deck's center line, but as much as 85 feet to the port side of that line. Since the normal approach to the carrier is in line with the center line of the angled landing deck, a lateral tilt of the "light plane" about the roll axis of the source light indicator assembly shifts the optical glide slope either up or down for those pilots who are approaching in line with the center line, depending on the direction of the tilt. The light plane is defined by the intersection of the FLOLS glide slope and the pitch axis of the source light indicator assembly. Figure 1-26 of reference 10 has an illustration of the light plane. This is reproduced here as figure 7.

Figure 7 illustrates three H/E roll angle functions and the resulting optical touchdown points. Figure 7(a) illustrates the H/E roll angle which corresponds to a rotation of zero degrees of the source light indicator assembly. Figure 7(b) illustrates the H/E roll angle which corresponds to a clockwise rotation of 7.5 degrees of the source light indicator assembly as viewed from the stern of the ship. Figure 7(c) illustrates the H/E roll angle which corresponds to a counterclockwise rotation of 7.5 degrees of the source light indicator assembly as viewed from the stern of the ship. A clockwise

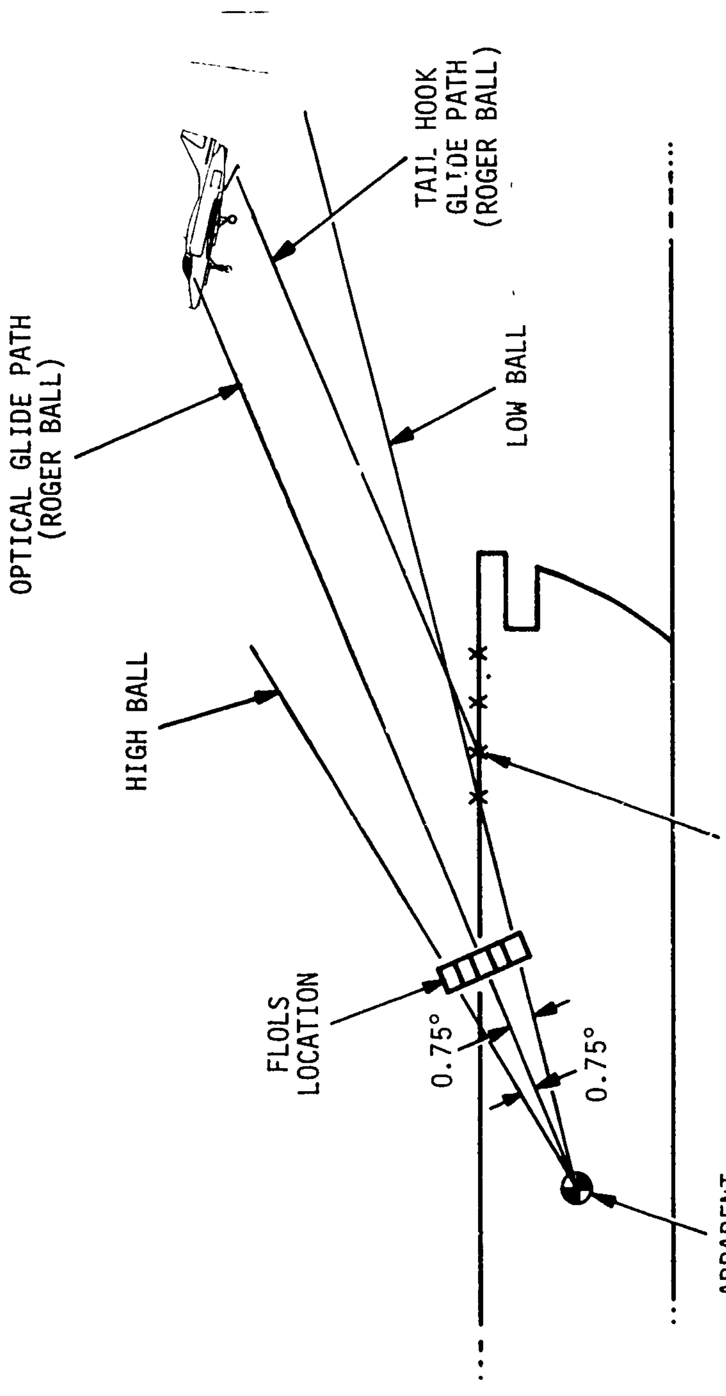


Figure 5. Carrier Approach Geometry

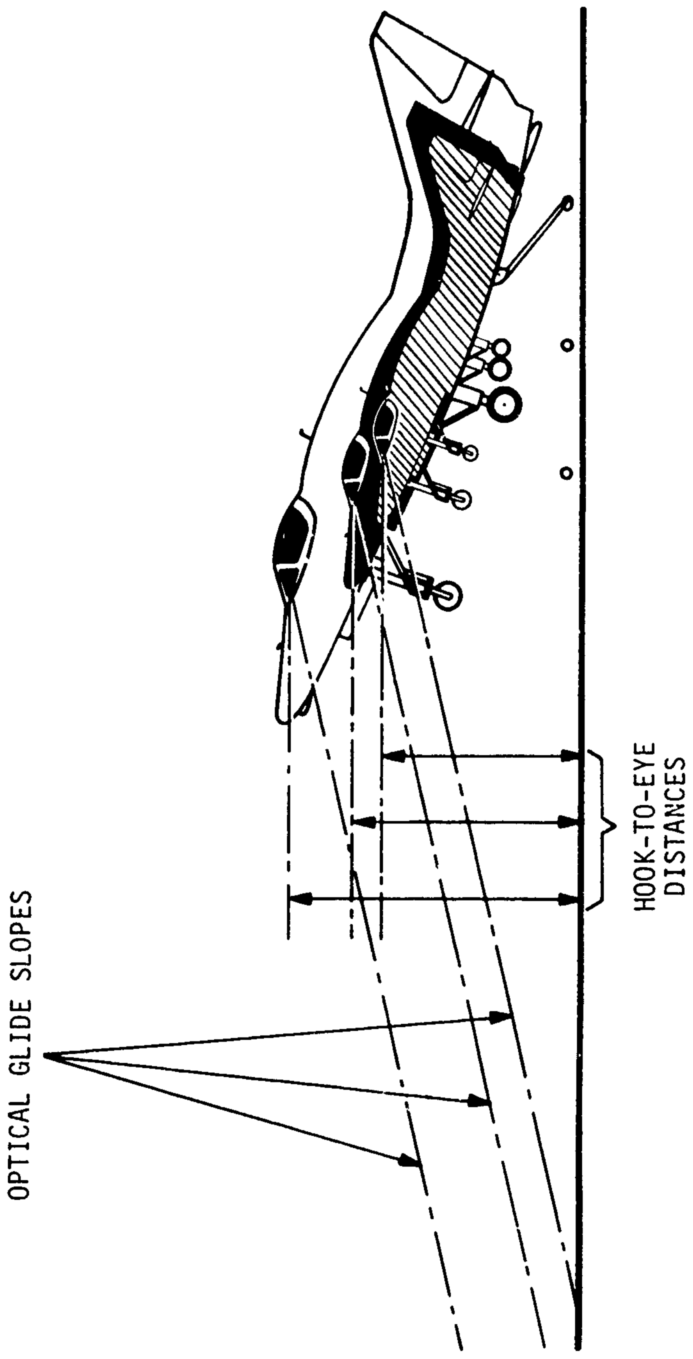


Figure 6. Glide Slope Angle and Hook-To-Eye Distance.

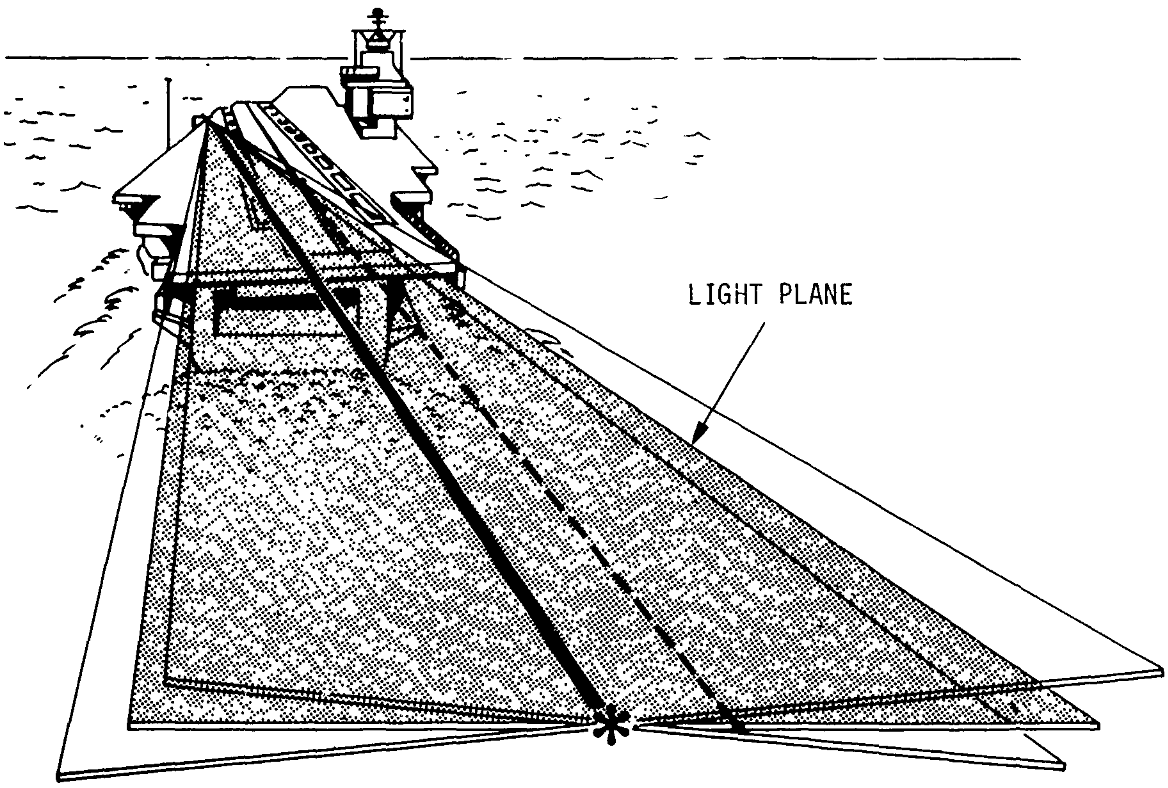


Figure 7(a). H/E Roll Angle Corresponding to Zero Degree Rotation of Source Light Indicator Assembly.

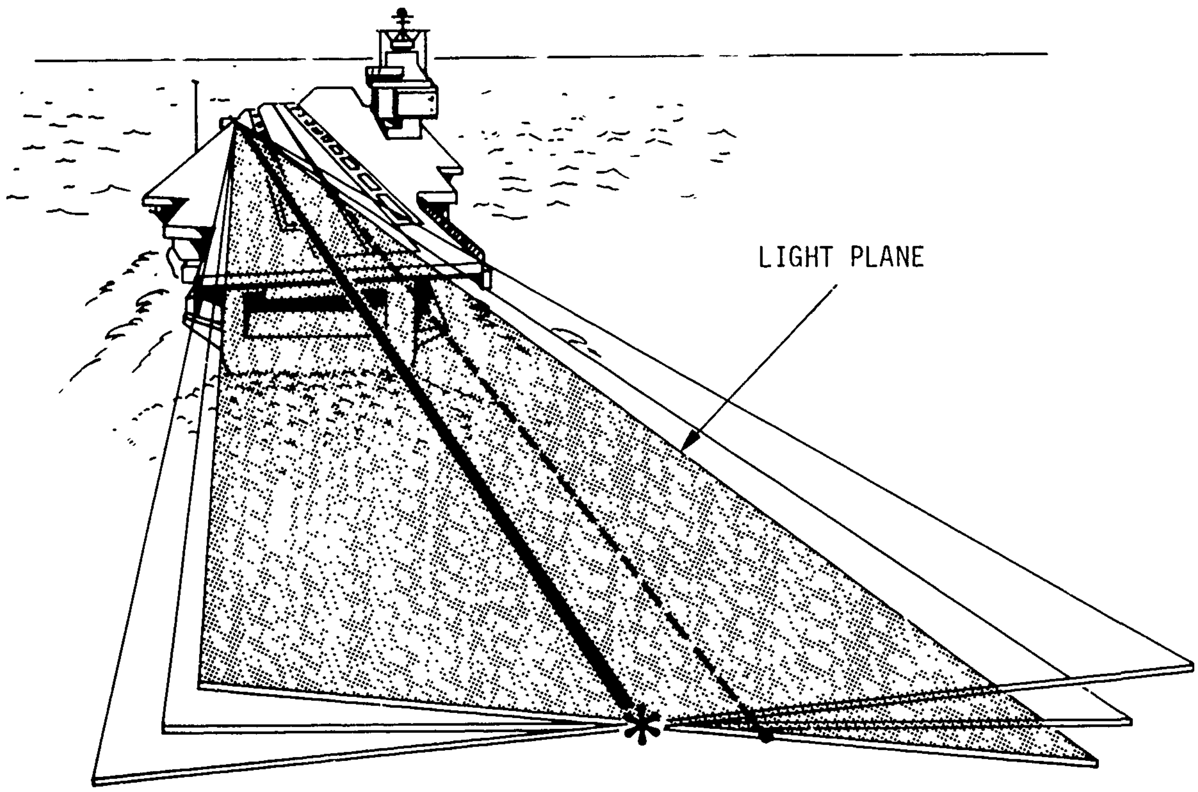


Figure 7(b). H/E Roll Angle Corresponding to 7.5 Degree Clockwise Rotation of Source Light Indicator Assembly.

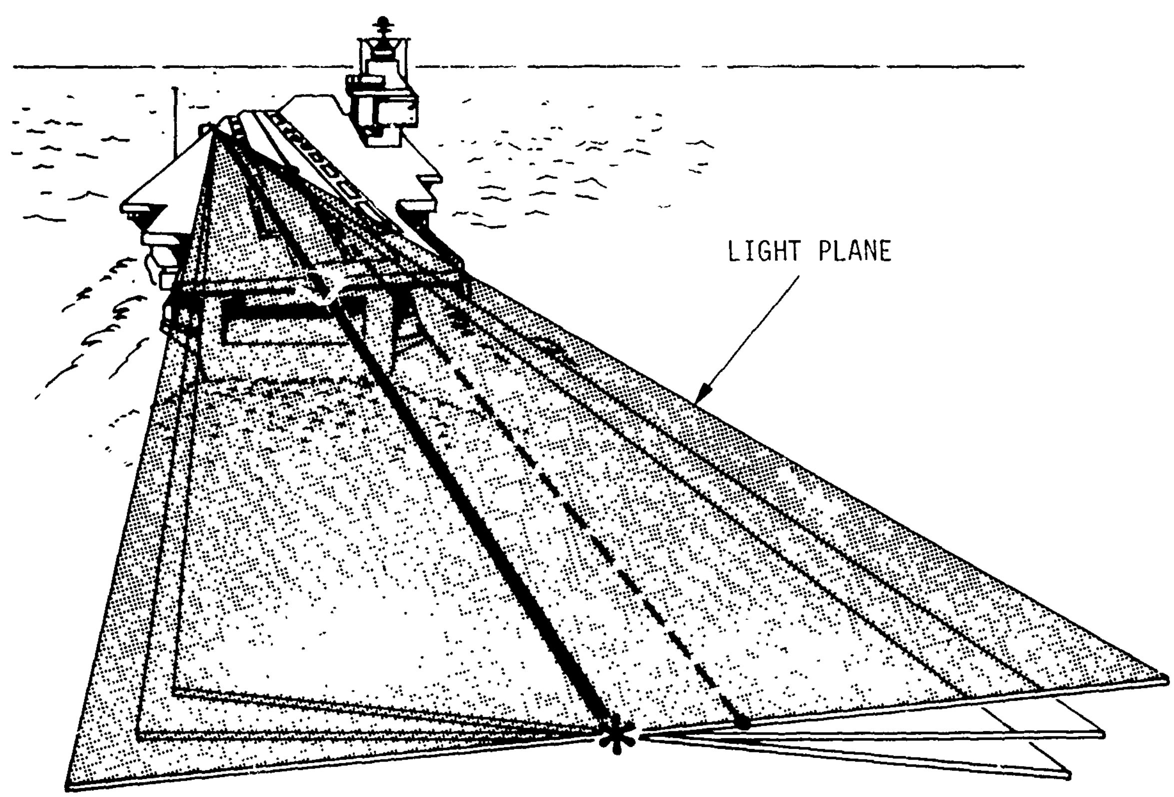


Figure 7(c). H/E Roll Angle Corresponding to 7.5 Degree Counterclockwise Rotation of Source Light Indicator Assembly.

rotation results in a downward shift of the optical glide slope, while a counterclockwise rotation results in an upward shift of the optical glide slope.

An important note in connection with the FLOLS is that it is imperative for the pilot to line up with the runway center line in making an arrested landing aboard the carrier, since the FLOLS does not provide line-up information. The preselected H/E roll angle function and resulting touchdown point is valid only when the pilot is lined up with the runway centerline.

The relationship between a change in optical glide slope angle and a change in source light indicator assembly roll angle depends upon the structural characteristics of the flight deck and location of the source light indicator assembly. Therefore, a recovery bulletin relating hook-to-eye distance and roll angle is furnished for each carrier. The purpose of this aircraft recovery bulletin is to give the basic angle and roll angle dial settings for the various types of aircraft expected to land on that particular carrier.

D. STABILIZATION

To compensate for the rolling and pitching motion of the ship, stabilization signals will drive the indicator unit to correct for roll and pitch. The MK 6 MOD 0 FLOLS has a point mode of stabilization, while the MK 6 MOD 1 or MOD 2 FLOLS has both point and line modes for stabilization. The point mode stabilizes the glide slope at a point 2,500 feet aft of the carrier, while the line mode will stabilize the glide slope all the way in to touchdown. With the point stabilization mode, the indicator unit (source light indicator assembly) is caused to rotate about its pitch axis in accordance with a stabilization signal. The line stabilization mode produces signals which through electronic circuitry drive the indicator unit to correct for roll and pitch with separate drives (2 degrees of freedom).

With either type of stabilization, the hook-to-eye value of the aircraft is corrected by rolling the indicator assembly. The H/E roll angle that is selected is not altered as a result of the stabilization signals. Neither is the glide slope angle. Once the basic pitch and the H/E roll angles are selected, they are maintained regardless of the pitch and roll of the carrier.

It should be noted that the Fresnel system cannot compensate for heave, which is the rise and fall of the entire ship without a change in pitch and roll angles. Therefore, a Landing Signal Officer is required to initiate a wave-off signal when the ship's heave becomes such that a landing is impractical.

SECTION V

CARRIER MATH MODEL

The following description of the carrier math model is preliminary to the presentation in Section VI of the carrier approach geometry and the FLOLS simulation equations.

A. DIMENSIONS

Figure 8 shows the significant dimensions of the aircraft carrier in the horizontal plane. The dimensions are tabulated in table 1. Figure 8 is not drawn to scale and does not include all details present in the display file.

The coordinate points PPP1 and CARR in the math model (see also figure 8) are defined as follows.

PPP1 - Used as the starting point for drawing the carrier deck. Located at the corner formed by the ramp and the starboard edge of the deck area.

CARR - Origin of the data definition coordinate system. In drawing the aircraft carrier, CARR is the only absolute point in the display file. Hence, all parts of the carrier are drawn relative to this coordinate.

Figure 9 also shows a top-down view of the carrier, but with the ship axis rotated by 8.08 degrees. This figure shows the carrier orientation as actually used in experiments. The reason for such a reorientation was to enable the pilots to land with an approximately zero degree aircraft heading. This was done by aligning the angled deck center line with the north-south axis. Due to the digital representation of data, the 7.95 degree rotation for an exact alignment was not possible; the nearest attainable value was the 8.08 degrees actually used.

Figure 9 also indicates the location of the FLOLS focal point. This is the computational point used to determine the apparent motion of the meatball landing device in response to glide path changes. The glide slope is set to originate at this coordinate point. An explanation of its use follows in the description of the FLOLS math model.

Figure 10 shows a vertical cross section of the carrier, with dimensions for deck level, arresting cables, FLOLS lens location, FLOLS focal point, PPP1, and CARR. As in the two previous illustrations, figures 8 and 9, the figure is not drawn to scale, and does not include all details present in the display file. Note that as in figure 9, the ship axis is rotated by 8.08 degrees. Table 2 lists the dimensions associated with figures 9 and 10.

B. LANDING OUTCOMES

TRAP Several conditions must be satisfied for a successful trap at touchdown. The following conditions are tested:

a. Aircraft Altitude - Z coordinate of aircraft CG (Center of Gravity). If the altitude is any value greater than 66 feet, the aircraft is flying higher than the carrier deck, and a landing is not feasible.

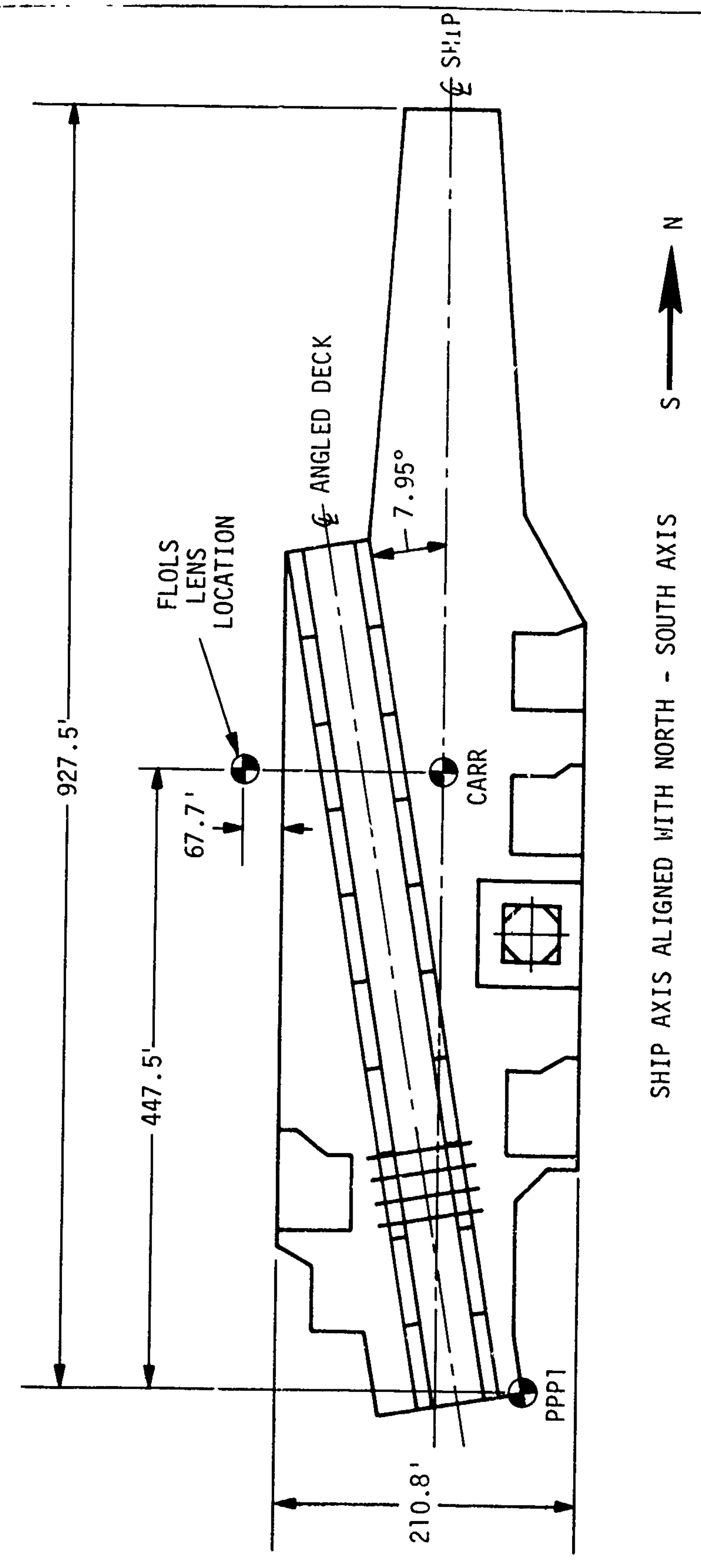


Figure 8. Carrier Dimensions.

TABLE 1. CARRIER DIMENSIONS IN THE HORIZONTAL PLANE

Total Length	-	927.5'
Total Width	-	210.8'
Angular Measurement between Center Lines of the Ship and Canted Deck	-	7.95^{0}
Lens Location, Optical Landing System	-	447.5' from PPP1 (ramp)
	-	67.7' from port edge of landing deck
Longitudinal Dimension	-	447.5' between points PPP1 and CARR

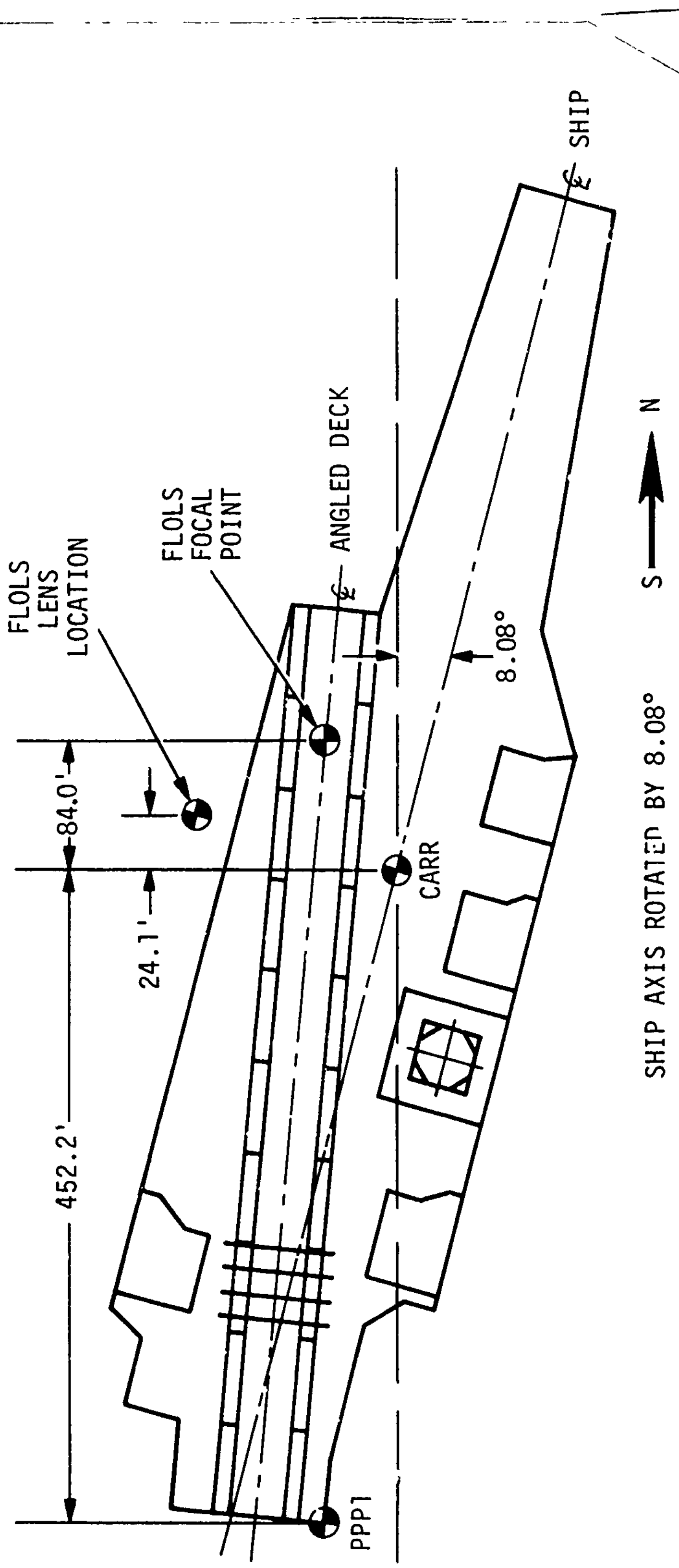
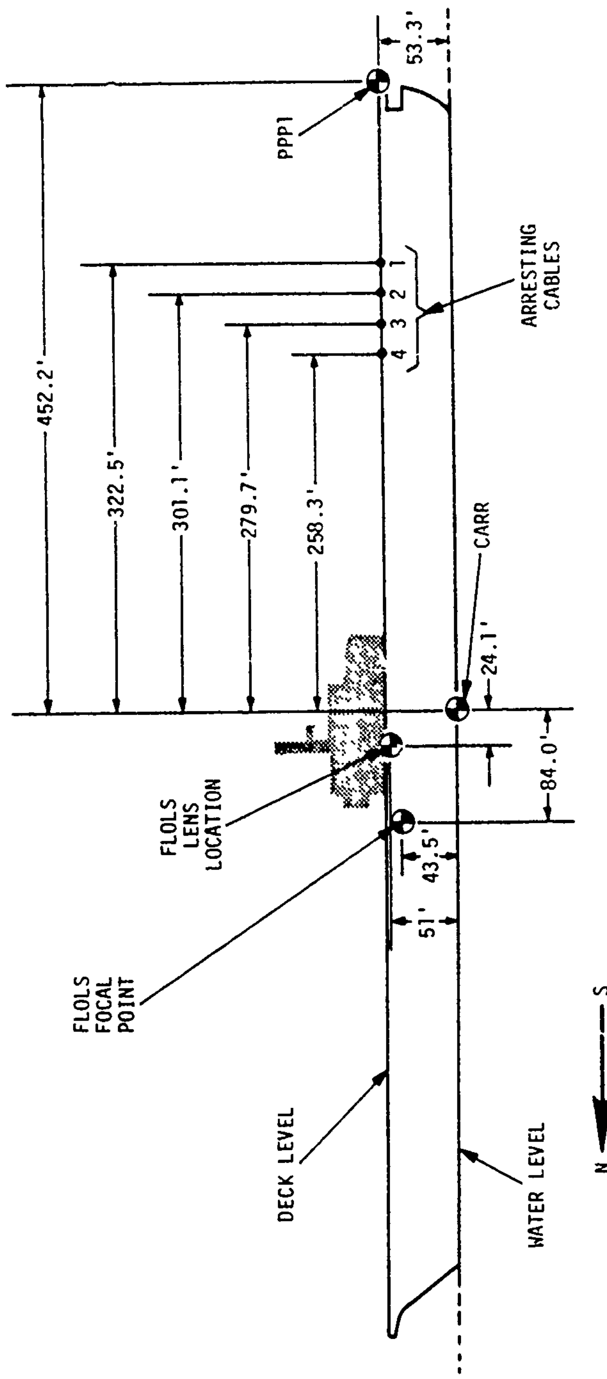


Figure 9. Top Down View of Carrier with 8.08 Degree Rotation



NORTH - SOUTH CROSS SECTION SHOWN ABOVE, WITH SHIP AXIS ROTATED BY 8.08°

Figure 10. Vertical Cross Section of Carrier

TABLE 2. CARRIER DIMENSIONS WITH 8.08 DEGREE ROTATION OF SHIP AXES

Deck Level	-	53.3' above sea level	
Arresting Cables, Ramp to Wire Distance	-	Cable 1	129.7'
		Cable 2	151.1'
		Cable 3	172.5'
		Cable 4	193.9'
FLOLS Focal Point	-	435.2' forward of ramp	
		43.5' above sea level	
FLOLS Lens Location	-	476.3' forward of ramp	
		117.8' to the left of the angled deck center line	
Location of CARR	-	452.2' forward of ramp	

Once however the altitude reaches 66 feet, the aircraft has achieved the proper altitude for landing. Note that with deck level being 53.3 feet above sea level, the aircraft CG is located 12.7 feet above the carrier deck at touchdown, as in figure 11.

b. Cable Zones - Tests for landing in cables zones. For these tests, the hook was assumed to be 10 feet back of the CG, as in figure 11. Figure 12 shows the angled deck runway in close-up view, with the dashed lines indicating the limits on the horizontal location of the CG for successful landing in cable zones 1, 2, 3, or 4. The longitudinal CG limits along the angled deck runway, as measured from CARR, were as follows:

ZONE	FROM	TO
1	330 feet	310 feet
2	310 feet	290 feet
3	290 feet	270 feet
4	270 feet	250 feet

The lateral limits on each side of the runway as measured from the reference point CARR were set to:

WAYLEFT limit = 76.3 feet.

WAYRIGHT limit = 26.3 feet.

c. Crash - Several conditions are tested in the time interval just prior to landing. Crashes occur for any of the conditons listed in the next paragraph.

CRASH The aircraft is crashed if when on the landing deck, or during approach to land:

a. The landing gear is not down and locked.

b. The rate of descent is greater than the maximum allowable value for landing (R/C $\leq$-1000 feet/minute).

c. The roll angle is too large, such that the wing tips contact the deck during roll ($-15^0 > \Phi > 15^0$).

d. The pitch angle is such that the nose wheel shock is fully compressed, or the tail is dragging along the ground during roll.

e. Maximum dynamic pressure is exceeded. A test checks for mach greater than the maximum allowable mach as a function of altitude.

f. Normal accelerations exceed structural limits. This occurs when the applied G is too negative or too positive. The limits on G are a function of mach and of gross weight.

g. Aircraft runs into side of carrier. This happens when the plane flies inside the carrier deck area with insufficient altitude for a landing, i.e., when the following conditions are all met:

X value of aircraft to CG is greater than MIN DECK X.

X value of aircraft CG is less than MAX DECK X.

Y value of aircraft CG is greater than MIN DECK Y.

Y value of aircraft CG is less than MAX DECK Y.

Altitude less than 66 feet.

BOLTER After a successful touchdown without capture, the aircraft altitude is restricted to 66 feet until a successful takeoff. There are several touchdown areas for bolter:

TOUCHDOWN AREA	TELETYPEWRITER MESSAGE
on deck, short of cables	'TOUCHDOWN SHORT'
on deck, overshot of cables	'TOUCHDOWN BEYOND CABLES'
left of cables	'TOUCHDOWN LEFT'
right of cables	'TOUCHDOWN RIGHT'

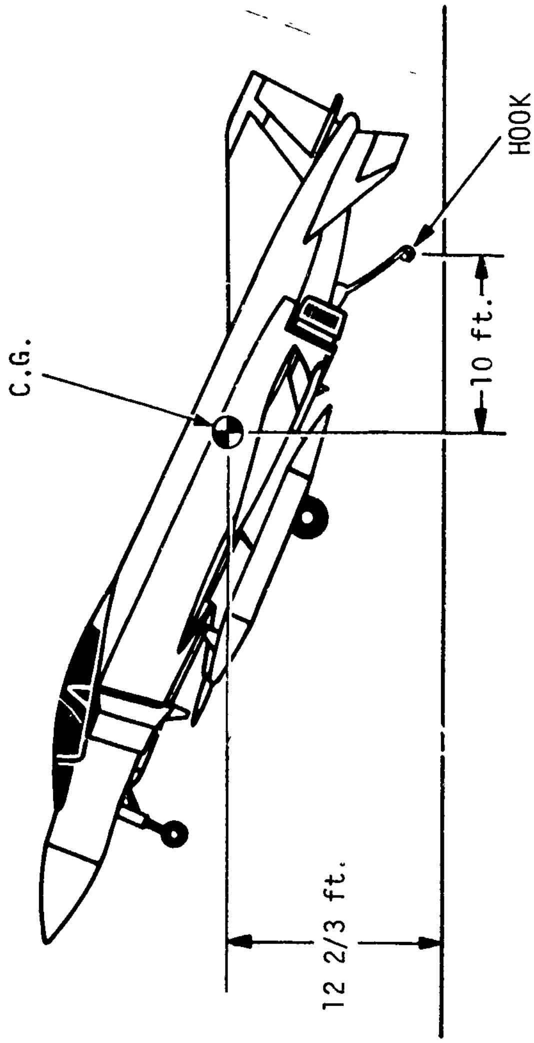


Figure 11. Hook-To-CG Distance in the Math Model.

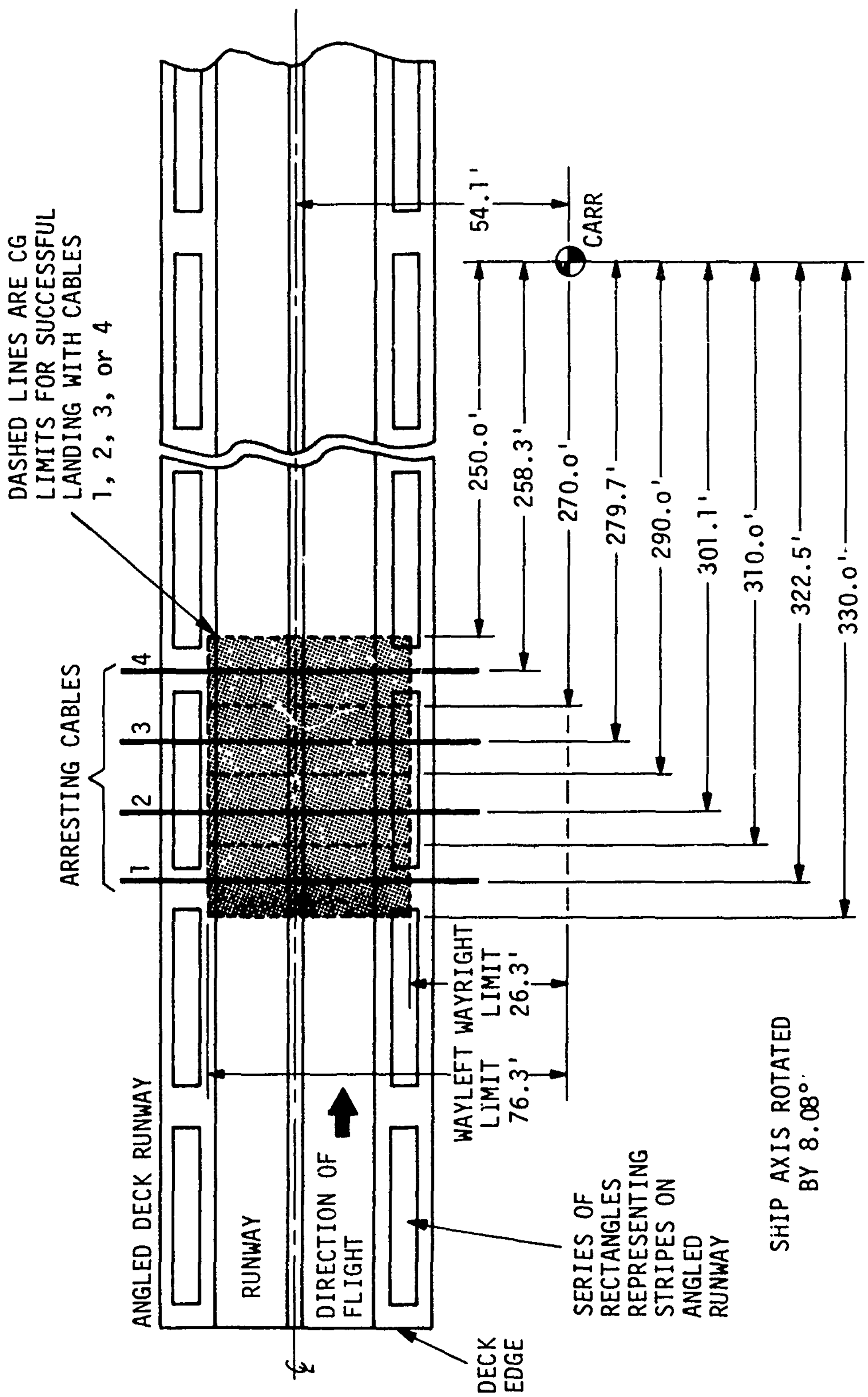


Figure 12. Cable Zones.

SECTION VI

FLOLS SIMULATION

The Fresnel system is represented by a stabilized system which is free from the pitch, roll, and heave inputs of the ship. This is so because the current mathematical model of the aircraft carrier does not include these variables. The system simulates a ± 90degree aximuthal range light beam inclined at a 3.53 degree angle relative to the center line of the angled deck, with the light source or 'meatball' visible for deviations of ± 0.75 degrees from the desired 3.53 degree glide slope.

MEATBALL DISPLACEMENT

Meatball displacement refers to the vertical position of the meatball with respect to the fixed horizontal row of datum lights. Error from glide path is presented to the simulator pilot as a vertical displacement between the moving meatball and the stationary datum arms. The meatball displacement is a function of the carrier approach geometry. Its computation requires information regarding the carrier dimensions, as found in section V of this report, and aircraft altitude and positional data for each computational cycle.

Figure 13 shows the X, Y, Z coordinate system for defining aircraft altitude and position. The carrier and the aircraft are viewed in both the vertical and horizontal planes. The definitions of the X, Y, and Z variables are as follows:

"X" is the linear distance in inches from the carrier's reference point CARR to the aircraft center of gravity (CG), measured along the north-south coordinate axis. Positive sense of direction is to the north, negative sense of direction to the south, such that X has a negative value for a landing approach from the south.

"Y" is the linear distance from CARR to aircraft CG along the east-west coordinate axis, with positive sense to the east.

"Z" is the aircraft altitude in inches, measured from sea level to aircraft CG, with positive sense of direction being up.

The governing equations for the meatball displacement are

$$\text{DEFLECT} = -\left(2\ \frac{\text{S.C. units}}{\text{inch}}\right) * (\text{MBFN}) \tag{1}$$

$$\text{MBFN} = \delta Z - \delta X * DZ/DX \tag{2}$$

where DEFLECT is measured in CRT scope coordinate units, and MBFN, δZ, δX DZ,DX are measured in inches.

A CRT scope coordinate unit is the unit of deflection in the screen coordinate system. In the Evans and Sutherland LDS-1, the number of different points that may be displayed along each axis is 4096. The position generators which determine the amount of deflection of the beam on the face of the CRT utilize digital-to-analog converters whose resolution is 12 bit in the X access (4096 positions) and 12 bit in the Y access (4096 positions).

Therefore, using 12 binary digits of precision provides an addressable area of 4096 x 4096 scope coordinate units on the display scope.

In addition,

$$DZ = Z + \Delta Z \tag{3}$$

$$DX = X + \Delta X \tag{4}$$

where ΔZ = vertical distance in inches from the FLOLS focal point to CARR.

ΔX = horizontal distance in inches from the FLOLS focal point to CARR.

DZ = vertical distance in inches from the FLOLS focal point to the aircraft CG.

DX = horizontal distance in inches from the FLOLS focal point to the aircraft CG.

These relationships are illustrated in figure 14.

δZ and δX are glide slope constants such that

$$\text{ARCTAN } (-\delta Z/\delta X) = \text{ glide slope angle in degrees.} \tag{5}$$

δZ and δX are also sensitivity constants for the vertical meatball displacement guaranteeing the relationship.

$$\underset{\text{(in meatball heights)}}{\text{VISUAL MEATBALL INDICATION}} = \left(\frac{8}{3}\ \frac{\text{meatball heights}}{\text{DEGREE}}\right) * \underset{\text{(in degrees)}}{\text{(ANGULAR DEVIATION)}} \tag{6}$$

This last equation shows the visual meatball indication to be directly proportional to the angular deviation of the aircraft from the ideal glide slope, with an 8 to 3 proportionality factor. Equation (6) applies to both the real system and the simulation.

DEFLECT is a numerical value for meatball displacement directly proportional to the angular deviation of the aircraft from the glide slope.

$$\underset{\text{(in S. C. units)}}{\text{DEFLECT}} = \left(149\ \frac{1}{3}\ \frac{\text{S.C. units}}{\text{degree}}\right) * \underset{\text{(in degrees)}}{\text{(ANGULAR DEVIATION)}} \tag{7}$$

Table 3 illustrates this relationship by listing several representative values for angular deviation, with a tabulation of corresponding values for DEFLECT, and the corresponding meatball indication to the pilot. Note the linear relationship between the three variables

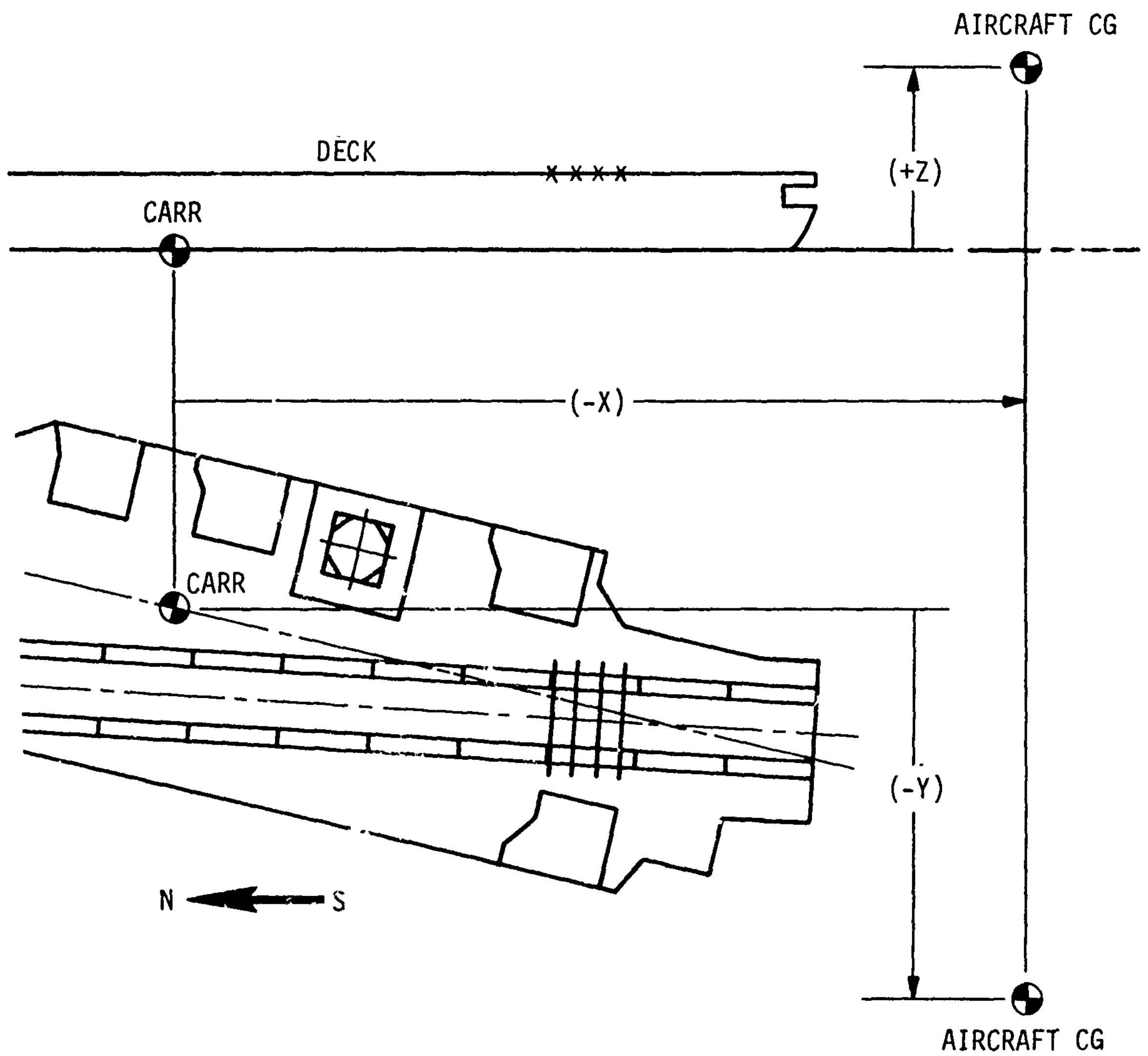


Figure 13. Definition of Position Coordinate System

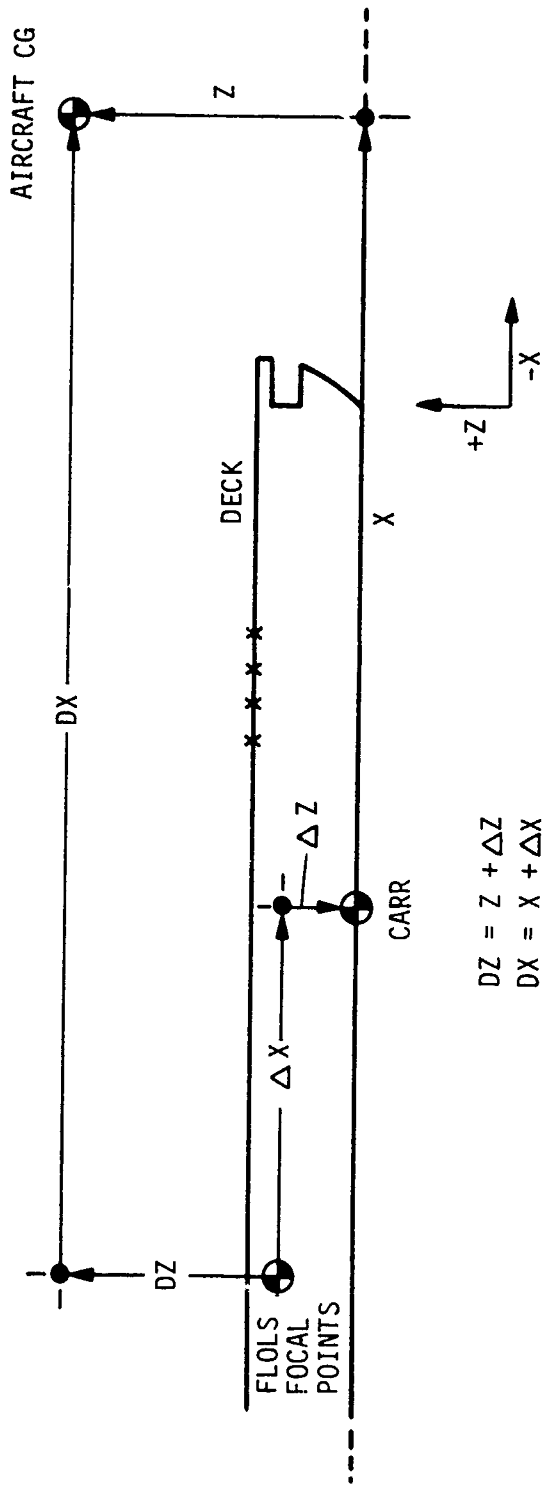


FIGURE 14. Positioning of FLOLS Focal Point.

TABLE 3. REPRESENTATIVE VALUES OF GLIDE SLOPE DEVIATION, ILLUSTRATING RELATIONSHIP BETWEEN ANGULAR DEVIATION, "DEFLECT," AND MEATBALL INDICATION.

Angular Deviation from Desired Glide Slope (degrees)	Computed Value of "DEFLECT" (scope coordinate) units	Visual Meatball Indication (meatball heights above or below horizontal reference bar)
$+0.75^{\circ}$	+112	meatball is 2 meatball heights above horizontal reference bars
$+0.375^{\circ}$	+56	one meatball height above
$+0.067^{\circ}$	+10	0.1785 meatball heights above
0.0°	0	meatball centered
-0.75°	-112	2 meatball heights below

MBFN is similarly a linear measure of meatball displacement and is inversely proportional to the angular deviation from the glide slope. MBFN is measured in inches, the basic unit of length in the simulation. The reason for two variables as measures of meatball displacement is the dual display of FLOLS. One display is an integral component of the three-dimensional carrier model, while a second display appears at the left hand edge of the CRT screen, as in figure 15. This second display is drawn in the 2-D operational mode of the LDS-1. Always positioned at the same scope coordinates on the left hand side of the screen, the 2-D version does not move, and unlike the 3-D version, its size does not change on the screen.

The purpose for this second FLOLS display is to ensure continued visibility of the FLOLS when the aircraft carrier is either quite far or quite near to the viewer. With the carrier more than approximately one mile from the viewer, the 3-D FLOLS display is too small to be useful because of its insensitive error indivation at long range. Conversely, when the carrier is close enough for the aircraft to be above the deck, the narrow 19 degree field of view on the CRT precludes the 3-D FLOLS from being seen.

MBFN and DEFLECT are meatball displacement values for the 3-D and 2-D FLOLS displays, respectively. The two functions differ with respect to sign and magnitude. Their opposite polarities are due to separate coordinate systems for the 3-D and 2-D displays, the down direction being positive in the former and negative in the latter. The difference in magnitudes of MBFN and DEFLECT exists because unlike the 2-D version, the 3-D FLOLS version is drawn to model scale.

The value for MBFN equals zero when the aircraft CG is on the prescribed ideal glide slope. This condition is expressed by equation (8) below. Substituting MBFN = 0 into equation (2).

$$0 = \mathrm{MBFN} = \delta Z - \delta X * (DZ/DX)$$

$$\frac{\delta Z}{\delta X} = \frac{DZ}{DX} \quad \text{aircraft exactly on glide slope} \qquad (8)$$

Equation (8) indicates that for the special condition of the aircraft exactly on the glide slope, the $\delta Z/\delta X$ ratio for the ideal glide slope is equal to the DZ/DX ratio of the aircraft glide slope.

The conditions for engaging the third arresting cable are as follows:

$$\delta Z = 264''$$

$$\delta X = -4280''$$

$$\Delta Z = -522''$$

$$\Delta X = -1008''$$

These given values for the constants δZ and δX provide the simulation a prescribed ideal glide slope of 3.53°, with a visual sensitivity on the CRT display in accordance with equation (6). The given values for the constants

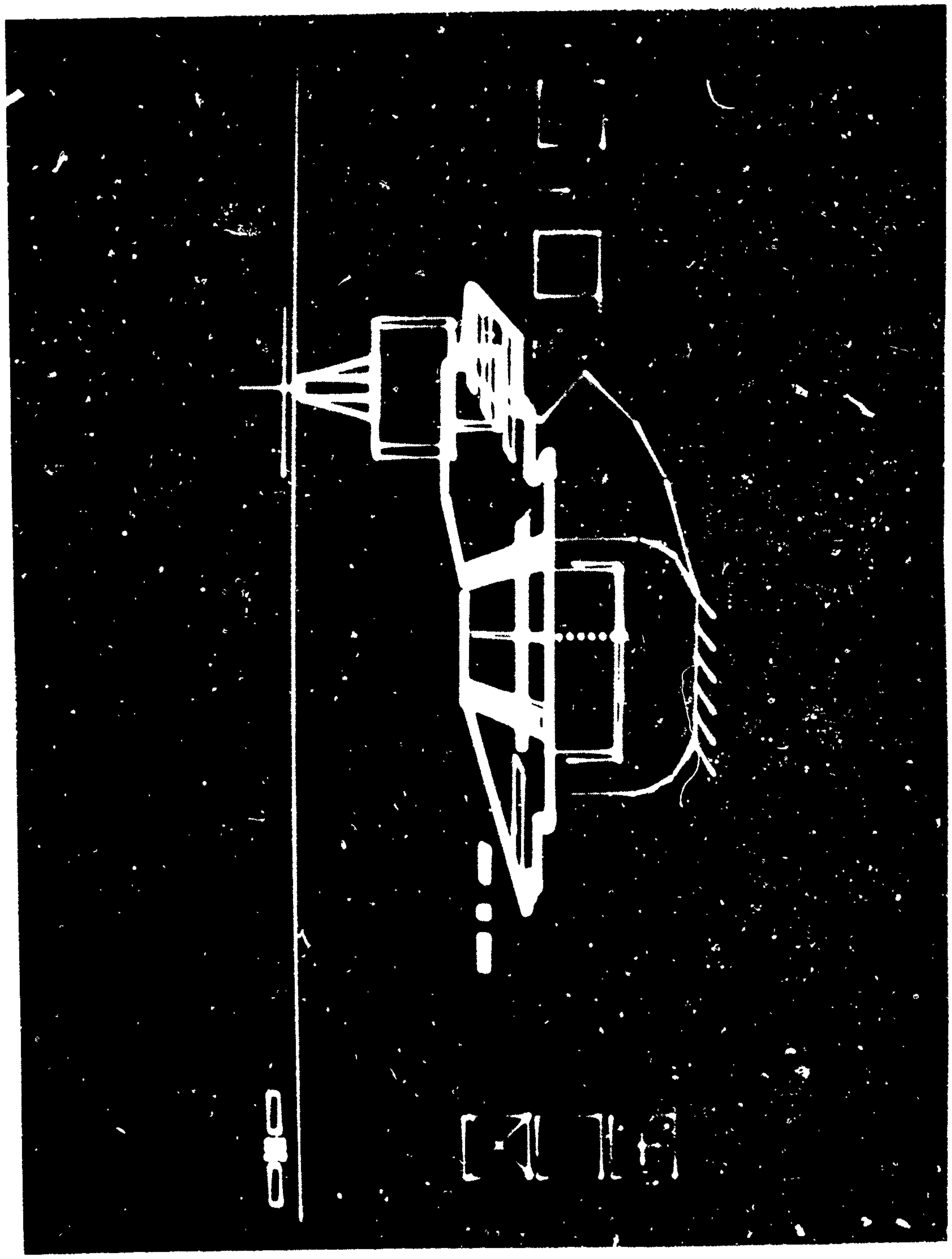


Figure 15. Duplicate FLOLS Displays

ΔZ and ΔX place the FLOLS focal point 522 inches above sea level and 1008 inches forward of the carrier reference point, as in figures 9 and 10.

In order to illustrate how the equations for the meatball displacement operate, several specific values for X and Z will now be substituted into equations (1) through (7)

Illustrative Example 1. In this first example, the aircraft has landed, and its center-of-gravity is positioned directly above the third wire.

$$X = -280 \text{ feet}$$

$$Z = +66 \text{ feet}$$

$$DZ = Z + \Delta Z = (66' * 12) + (-522'') = 270''$$

$$DX = X + \Delta X = (-280' * 12) + (-1008'') = -4368''$$

$$MBFN = \delta Z - \delta X\ (DZ/DX) = 264'' - (-4280'') * \left(\frac{270''}{-4368''}\right)$$

$$= -0.56''$$

$$DEFLECT = (-2) * (MBFN) = (-2) * (-.0.56'') = 1.12 \text{ S.C. units}$$

$$\text{ANGULAR DEVIATION FROM GLIDE SLOPE} = DEFLECT/149\tfrac{1}{3} = .0075^{0}$$

$$\text{VISUAL MEATBALL INDICATION} = 8/3 \text{ ANGULAR DEVIATION FROM GLIDE SLOPE}$$

$$= 8/3 * (.0075^{0}) =$$

$$= 0.02 \text{ meatball heights above center}$$

$$\text{GLIDE SLOPE} = \text{ARCTAN}\left(\frac{-\delta Z}{\delta X}\right) = \text{ARCTAN}\left(\frac{-264''}{4280''}\right) = 3.53^{0}$$

Illustrative Example 2. In this example, the aircraft has landed and the hook is engaged by the third wire.

$$X = -270 \text{ feet}$$

$$Z = 66 \text{ feet}$$

DZ = 270"

DX = -4248"

MBFN = -8.03"

DEFLECT = 16.06 scope coordinate units

ANGULAR DEVIATION FROM GLIDE SLOPE = $.05^{0}$

VISUAL MEATBALL INDICATION = 0.14 meatball heights above center

Table 4 shows the visual meatball indication as a function of several sets of specific X and Z values. The first set of values corresponds to a situation where the aircraft is on the flight deck (z = 66'). The second group corresponds to the aircraft located approximately 1.5 nautical miles from the third wire on the flight deck (X = -9347'). Note that when the aircraft CG is directly above either the first or second wires, the meatball is low; when the CG is directly above the third wire, the meatball is practically centered; and when the CG is directly above the fourth wire, the meatball is high.

Aircraft CG Above Wire #	Visual Meatball Indication
1	0.92 meatball heights below
2	0.47 meatball heights below
3	0.02 meatball heights above
4	0.57 meatball heights above

Illustrative Example 3. In this example, the aircraft is at a distance of 1.5 nautical miles from the fourth wire. The view from that distance, and the corresponding meatball indication, are shown in figure 16.

X = -9347 feet

Y = - 500 feet

Z = + 710 feet

DZ = Z + Δ Z = (710' * 12) + (-522") = 7998"

DX = X + Δ X = (-9347' * 12) + (-1008") = -113,172"

MBFN = δ Z - δ X *(DZ/DX) = 264" - (-4280") * $\left(\frac{7998''}{-113{,}172''}\right)$ = 38.5"

DEFLECT = (-2) * (MBFN) = (-2) * (-38.5") = 77.0 s.c. units

ANGULAR DEVIATION FROM GLIDE SLOPE = DEFLECT/$149\frac{1}{3}$ = +77.0/$149\frac{1}{3}$

= + 0.515^{o}

VISUAL MEATBALL INDICATION = 8/3 ANGULAR DEVIATION FROM GLIDE SLOPE =

= 8/3 * (0.515^{o}) = 1.37 meatball heights above center

TABLE 4. VISUAL MEATBALL INDICATION AS FUNCTION OF SELECTED X AND Z VALUES.

X (feet)	Z (feet)	DEFLECT (SCOPE COORDINATE UNITS)	ANGULAR DEVIATION FROM GLIDE SLOPE (degrees)	VISUAL MEATBALL INDICATION (meatball heights above center)
-260'	66'	31.88	0.21°	0.57
-270'	66'	16.06	0.05°	0.14
-280'	66'	1.12	0.01°	0.02
-290'	66'	-13.03	-0.09°	-0.23
-300'	66'	-26.44	-0.18°	-0.47
-320'	66'	-51.26	-0.34°	-0.92
-9347'	610'	-13.86	-0.09°	-0.25
-9347'	625.23'	0	0°	0
-9347'	748.62'	112	0.75°	2.0

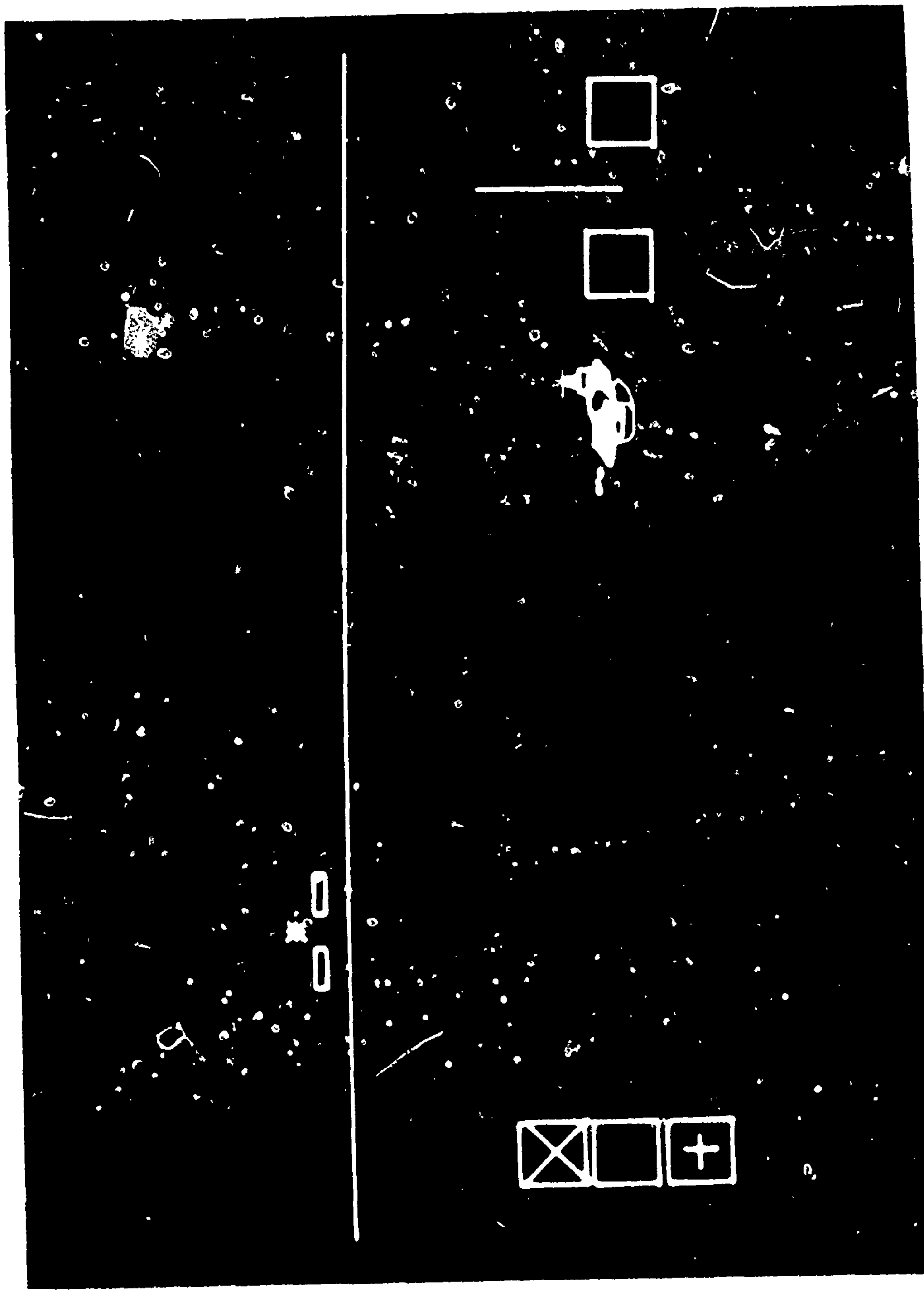


Figure 16. View of Carrier at 1.5 Nautical Miles

DISPLAY CONFIGURATION

There are two displays of the FLOLS in the carrier landing simulation. One display appears next to the carrier, while a second display is stationed on the left side of the screen (see figure 15). The second display remains stationary at a constantly displayed size and may be used if needed when the meatball of the first display is either invisible or not clearly visible to the simulator pilot. The meatball of the three-dimensional FLOLS display, which is adjacent to the carrier, is not visible over the entire range of operation.

The location of the FLOLS for the aircraft carrier is illustrated in figures 8, 9, and 10. The lens is shown to be 476.3 feet forward of the angled deck ramp, and 117.8 feet to the left of the angled deck center line.

Figure 17 shows the FLOLS displays for both the three-and two-dimensional models. The meatball is drawn as an eight-pointed star, and the horizontal datum lights are represented by fixed index bars. The figure shows dimensional data as well.

OTHER FEATURES

The meatball is drawn only if the plane is aft of the meatball display. The effect is the simulation of $\pm 90^{\circ}$ azimuthal range light beam.

Above a 4.28° glide slope the meatball is no longer displayed. (4.28° = $3.53 + 0.75^{\circ}$). At 4.28°, the meatball is at the top of its travel (two meatball heights above center). At 3.53°, the meatball is at its origin, while at 2.78° ($3.53^{\circ} - 0.75^{\circ}$) it is positioned at the bottom of its allowable travel. It is not displayed below 2.78°.

To facilitate the detection of low meatball, the meatball is displayed with a brighter intensity between $3.53^{\circ}$and 2.78°, so that the simulator pilot views a brighter meatball below the prescribed glide slope.

The following features are lacking in the present system:

a. The actual FLOLS has a yellow meatball and green datum lights. The The TRADEC LDS-1 system on the other hand has no color.

b. Flashing red meatball condition for dangerously low approach.

c. Wave-off signal for unsafe landing condition.

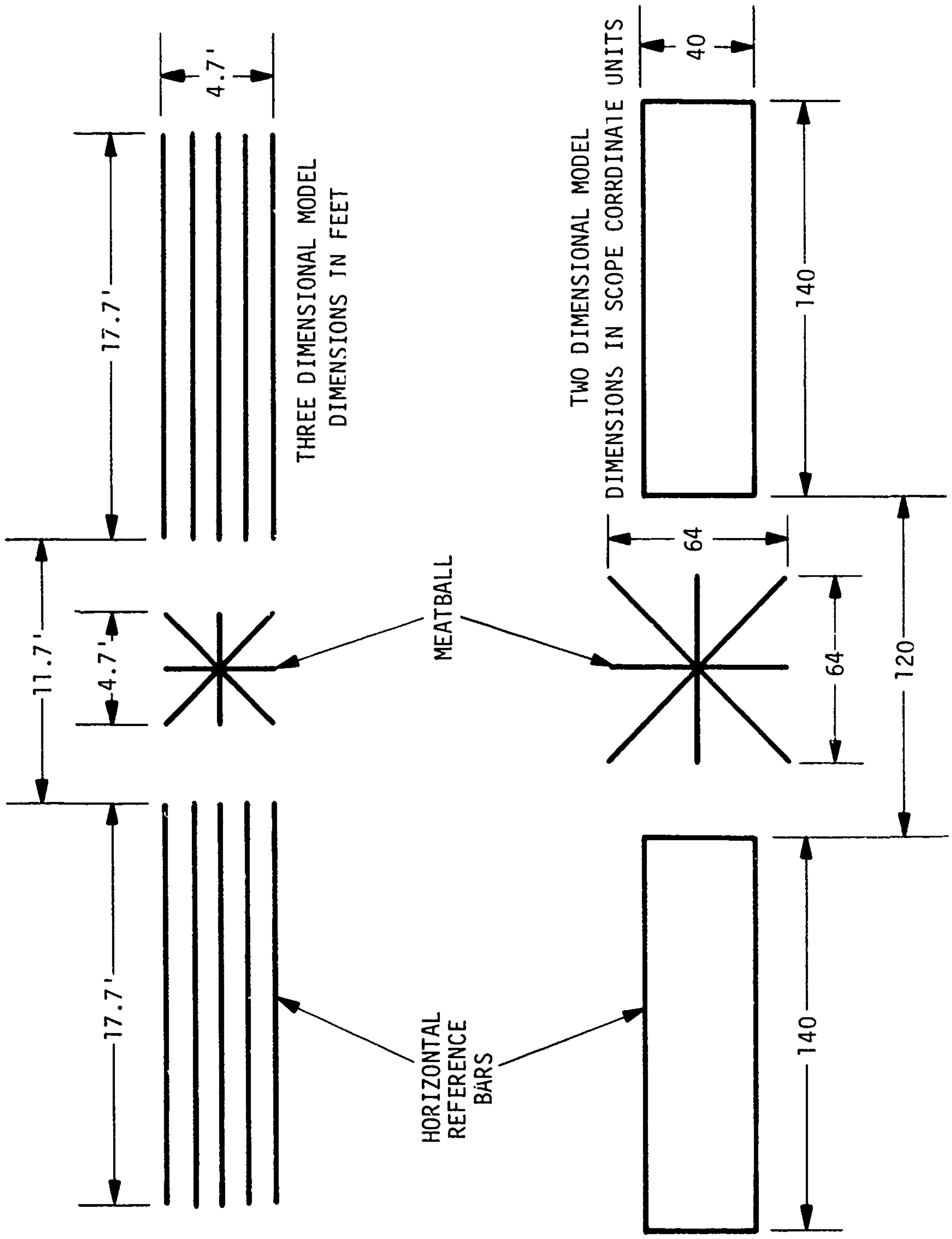


Figure 17. Visual Simulation of Deck Edge Assembly.

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